CHAPTER 9

CANTILEVER REINFORCED CONCRETE WALLS

9-1. General Characteristics. The cantilever reinforced concrete wall is a special type of gravity wall in which part of the stabilizing weight is supplied by the weight of the backfill resting on the base slab. The structural members are designed for stresses due to bending and shear. Chapter 2, Section I, offers additional general comments on cantilever concrete walls.

9-2. Foundation Investigation. The requirements for the foundation investigation are discussed in Chapter 2, Section V.

9-3. Materials. Concrete materials and mixture proportioning, with appropriate water-cement ratios for durability, should follow guide specification CW 03301 and EM 1110-2-2000. Typically, a concrete compressive strength of 3,000 psi is used for retaining walls. The age at which the specified strength is to be obtained should be decided by the designer depending on the loading conditions anticipated. Steel reinforcement bars should follow the specifications in the American Concrete Institute (ACI) Building Code (ACI 318), with the exception that for hydraulic structures the grade of steel will be limited to ASTM Grade 60 without special approval.

9-4. Reinforcement Cover. For hydraulic structures the minimum reinforcement cover should comply with EM 1110-2-2103. For structures not subject to hydraulic action the minimum reinforcement cover should comply with the ACI Building Code requirements.

9-5. Load Cases. The load cases should be those described in Section I of Chapter 4. The magnitude and distribution of the loads should be determined as described in Chapter 3.

9-6. Structural Stability. Sliding and overturning stability should be determined by the methods and criteria discussed in Chapter 4. Forces and moments for structural design should be based on external forces allocated according to paragraphs 3-7 through 3-9 and calculated as described in Section III of Chapter 4 for overturning stability. Sample stability calculations are shown in Appendix N.

9-7. Structural Design.

a. General. Reinforced concrete walls should be designed for the loading cases given in Section I of Chapter 4 and the foundation pressures obtained from the overturning stability analysis described in Section III of Chapter 4. Wall components should be analyzed as cantilever beams. Compression reinforcement is not normally used. Temperature and shrinkage reinforcement should conform with EM 1110-2-2103. Example calculations are shown in Appendix N. When the top surface of backfill is sloping upward, a shear force in addition to the horizontal earth force should be considered acting on the structural wedge (see Figure 9-1).

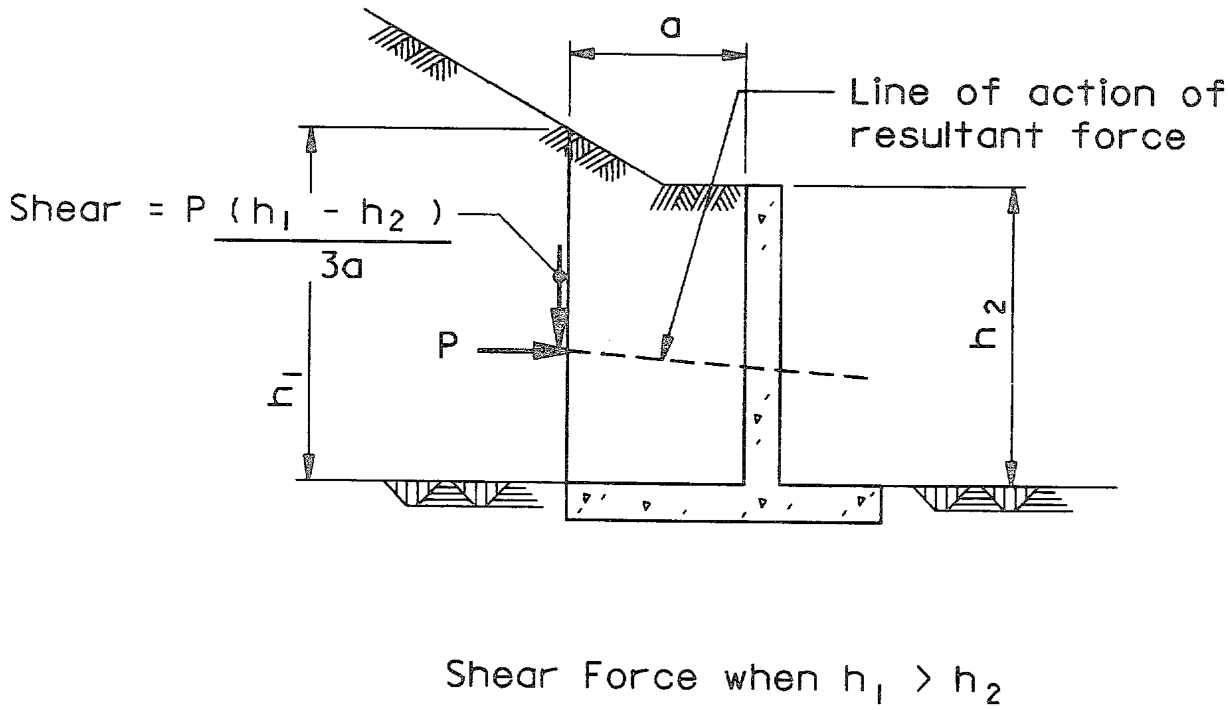


Figure 9-1. Shear force for upward-sloping backfill

b. <u>Stem</u>. Axial loads are usually small and may be neglected in design.

c. <u>Toe</u>. The toe should be designed with loads imposed by soil, water, concrete, bearing pressures, etc. The effects of axial loads are not ordinarily substantial enough to be taken into account.

d. <u>Heel</u>. The loads for calculating design moments are the weight of soil, water, and concrete acting downward, along with uplift and bearing pressure acting upward. The bearing pressure should be determined using the horizontal earth force and shear when the backfill surface is sloping upward (see paragraphs 9-7a and 4-8c). With no key, the base shear should be neglected when computing reinforcement, as illustrated in Appendix N, example 1.

e. <u>Special Considerations for Walls with Keys</u>. The overturning stability criteria for walls with keys include an assumed uniform distribution of earth pressure on the resisting side of the key that may result in unconservative design for reinforcement in the top face of the wall heel at and near the face of the stem. A portion of this force may actually act along the plane at the base slab of the wall and not on the key. The designer is cautioned to consider this in developing a reinforcing design. A conservative approach for design of the heel top steel at the stem would result from the use of foundation pressures obtained from a stability analysis assuming that all of the earth resistance acts along the plane at the base of the wall. See Section III of Chapter 4, especially paragraph 4-8b. Stability calculations for walls with keys are shown in examples 3 and 6 of Appendix N.

9-8. Reinforced Concrete Design.

a. General. Reinforced concrete walls should be designed with the strength design method in accordance with the current ACI Building Code, except as herein specified. Notations used are the same as those in the ACI Code, except those defined herein. (Appendix D lists the Notation used in Chapter 9.) WES Technical Report SL-80-4 (Liu and Gleason 1981) contains design aids consistent with the information presented in paragraph 9-8b of this chapter. Retaining walls and flood walls may be designed using the same load factor for concrete weight as that selected for earth and water loads, as explained in paragraph 9-8b(1), Equations 9-5 and 9-6.

b. Hydraulic Structures--Strength and Serviceability.

(1) Required Strength. Reinforced concrete hydraulic structures should be designed to have strengths in all sections equal at least to those calculated for the factored loads and forces in the following combinations that are applicable.

(a) For usual loading cases R1, I1, C1, C2a, and C2c as described in Chapter 4:

$$U = 1.5D + 1.9L \quad (\text{if } D \text{ and } L \text{ have the same sign}) \qquad [9\text{-}1]$$

or

$$U = 0.9D + 1.9L \quad (\text{if } D \text{ opposes } L) \qquad [9\text{-}2]$$

where

D = internal forces and moments from dead load of the concrete members only

L = internal forces and moments from live loads (loads other than the dead load of concrete members)

(b) For unusual or extreme loading conditions such as cases R2, R3, I2, I3, I4, C2b, C3, C4, and C5, earthquakes, and short-term loadings:

$$U = 0.75(1.5D + 1.9L) \quad (\text{if } D \text{ and } L \text{ have the same sign}) \qquad [9\text{-}3]$$

or

$$U = 0.75(0.9D + 1.9L) \quad (\text{if } D \text{ opposes } L) \qquad [9\text{-}4]$$

(c) In most retaining walls and flood walls, dead loads represent a small percentage of total loads and the additional effort to recompute another stability analysis using the above two factors may not be warranted. Therefore, a single load factor as defined by Equation 9-5 may be substituted for Equations 9-1 and 9-2 to avoid having to recompute an alternate stability analysis with a different set of loadings. Likewise, Equation 9-6 may be substituted for Equations 9-3 and 9-4.

$$U = 1.9(D + L) \qquad [9\text{-}5]$$

$$U = 0.75[1.9(D + L)] \qquad [9\text{-}6]$$

Note that the ACI definition of D is modified so that

D = dead load of the concrete members only or related axial forces, shears, and moments

L = all loads other than dead load of concrete, or related axial forces, shears, and moments

(d) When multiple load factors are used and the reactions (i.e., base reactions, pile reactions, resisting earth pressures, etc.) are computed using the applied factored loads, the following combinations should be considered:

From Equation 9-1: $U = 1.5D + 1.9L + R_f$ [9-7]

From Equation 9-2: $U = 0.9D + 1.9L + R_f$ [9-8]

From Equation 9-3: $U = 0.75(1.5D + 1.9L + R_f)$ [9-9]

From Equation 9-4: $U = 0.75(0.9D + 1.9L + R_f)$ [9-10]

where R_f equals internal forces and moments resulting from reactions induced by the applied factored dead and live loads.

(e) When the single load factor is used and the reactions (i.e., base reactions, pile reactions, resisting earth pressures, etc.) are computed using the applied unfactored loads, the following combinations should be considered: (See paragraphs j and k, Example 1, Appendix N).

From Equation 9-5: $U = 1.9(D + L + R)$ [9-11]

$$\text{From Equation 9-6: } U = 0.75[1.9(D = L + R)] \qquad [9\text{-}12]$$

where R equals internal forces and moments resulting from reactions induced by applied unfactored dead and live loads.

(2) Design Strength of Reinforcement. The design should be based on yield strengths of reinforcement of 40,000 psi and 48,000 psi for ASTM Grades 40 and 60 steels, respectively, except for calculating development lengths. The development length for Grades 40 and 60 steels should be based on yield strengths of 40,000 psi and 60,000 psi, respectively. Reinforcement with a yield strength in excess of Grade 60 should not be used unless a detailed investigation of ductility and serviceability requirements is conducted in consultation with and approved by Headquarters, US Army Corps of Engineers (HQUSACE) (CECW-ED).

(3) Maximum Tension Reinforcement. For flexural members and for members subject to combined flexure and compressive axial load when the design load strength ϕP_n is less than the smaller of $0.10f'_c A_g$ or ϕP_b, the ratio of tension reinforcement provided generally should not exceed $0.25\rho_b$. Reinforcement ratios greater than $0.25\rho_b$ but less than $0.50\rho_b$ may be used in retaining walls if excessive deflections are not predicted when using the method specified in the ACI Building Code. Reinforcement ratios in excess of $0.50\rho_b$ should not be used unless a detailed investigation of serviceability requirements, including computation of deflections, is conducted in consultation with and approved by HQUSACE (CECW-ED).

(4) Minimum Reinforcement of Flexural Members. At any section of a flexural member where reinforcement is required by analysis, the minimum reinforcement requirements specified in the ACI Building Code, should apply, except that f_y should be in accordance with paragraph 9-8b(2).

(5) Control of Deflections and Cracking. Cracking and deflections due to service loads need not be investigated if the limits on design strength specified in paragraph 9-8b(2) and a reinforcement ratio of $0.25\rho_b$ are not exceeded. Where these limitations are exceeded, extensive investigation of deformation and cracking due to service loads should be made in consultation with higher authority.

(6) Distribution of Flexural Reinforcement. The spacing of flexural tension reinforcement should not generally exceed 18 inches for Grade 40 steel, or 12 inches for Grade 60 steel.

(7) Extreme Loadings. For extreme loadings which are highly improbable, such as from earthquakes which have a frequency of occurrence that greatly exceeds the economic life of the structure, selection of less conservative load factors than given in Equations 9-3, 9-4, and 9-6 and less conservative

strength criteria than given above may be justified. For extreme loadings, requests and the justification for varying from the guidance should be submitted to HQUSACE (CECW-E) for approval.

c. Hydraulic Structures--Reinforced Concrete Design.

(1) Design Assumptions.

(a) Strain. The assumed maximum usable strain at the extreme concrete compression fiber should be equal to 0.003. The design strain ε_m at the extreme concrete compression fiber should be limited to 0.5 of the maximum usable strain for hydraulic structures.

(b) Balanced Conditions. Balanced conditions exist at a cross section when the tension reinforcement reaches the strain corresponding to its specified yield strength f_y just as the concrete in compression reaches its design strain ε_m . T-wall members should be designed for a ductile failure on the tensile side of balance, as described in paragraphs 9-7a, 9-8b(3), and 9-8b(4).

(c) Concrete Stress. A concrete stress of $0.85f'_c$ should be assumed uniformly distributed over an equivalent compression zone bounded by the edges of the section and a straight line lying parallel to the neutral axis at a distance $a = \beta_m c$ from the extreme compression fiber. The factor β_m should be taken as 0.55 for values of f'_c up to 4,000 psi. For values of f'_c greater than 4,000 psi, β_m should be 0.50.

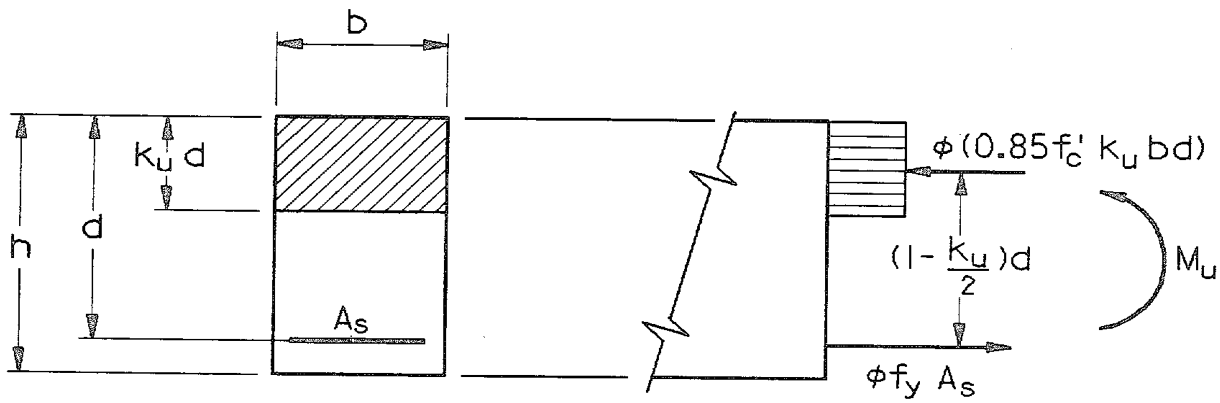
(2) Design Equations. Equations for design and investigation of reinforced concrete sections are given in Figures 9-2 through 9-5. These will be the only equations required to determine flexural adequacy for sections of retaining and flood walls in practically all cases.

(a) The minimum effective depth (d) needed to provide the amount of ductility required by criteria may be determined from the following equation

$$d_{min} = \sqrt{\frac{M_u/\phi}{0.85f'_c k_m b\left(1 - \frac{k_m}{2}\right)}} \qquad [9\text{-}13]$$

where

$$k_m = \frac{f_y \rho_{max}}{0.85f'_c}\ ,\ \rho_{max} = \lambda \rho_b$$



DESIGN

GIVEN : M_u, b, d, h, f_y, f'_c, $\phi = 0.9$

FIND: k_u, A_s AND ρ

$$k_u = 1 - \sqrt{1 - \frac{M_u}{0.425 \phi f'_c bd^2}} \quad , \quad A_s = \frac{0.85 f'_c k_u bd}{f_y}$$

$$\rho = \frac{A_s}{bd} \leq \rho_{MAX} \quad , \quad \rho = \frac{0.85 f'_c k_u}{f_y}$$

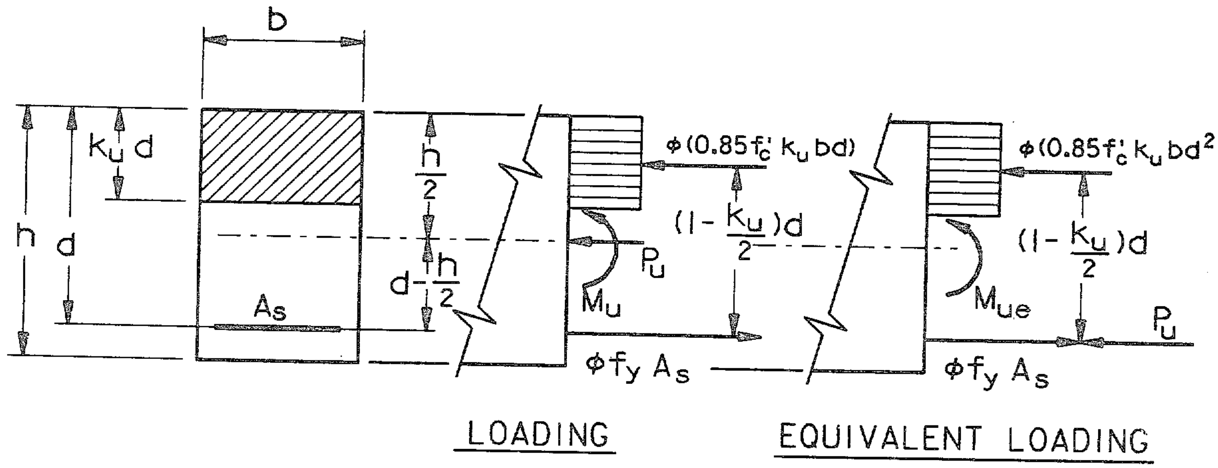
INVESTIGATION

GIVEN : b, d, h, f_y, f'_c, $\phi = 0.9$, A_s, $\rho = \frac{A_s}{bd} \leq \rho_{MAX}$

FIND: k_u AND M_u

$$k_u = \frac{f_y \rho}{0.85 f'_c} \quad , \quad M_u = \phi f_y \rho \left(1 - \frac{f_y \rho}{1.7 f'_c}\right) bd^2$$

Figure 9-2. Rectangular beam, simple bending with no compression reinforcement



FOR EQUIVALENT LOADING: $M_{ue} = M_u + P_u\left(d - \frac{h}{2}\right)$

DESIGN

GIVEN : P_u, M_u, b, d, h, f_y, f'_c,

(ϕ SHALL NOT BE LESS THAN 0.7) $\phi = 0.9 - \left(\frac{P_u}{0.1 f'_c bh}\right)(0.2)$

FIND: k_u, A_s AND ρ

$$k_u = 1 - \sqrt{1 - \frac{M_{ue}}{0.425\,\phi\, f'_c\, bd^2}} \quad , \quad A_s = \frac{0.85 f'_c k_u bd - \frac{P_u}{\phi}}{f_y}$$

$$\rho = \frac{0.85 f'_c k_u - \frac{P_u}{\phi bd}}{f_y} \leq \rho_{MAX}$$

INVESTIGATION

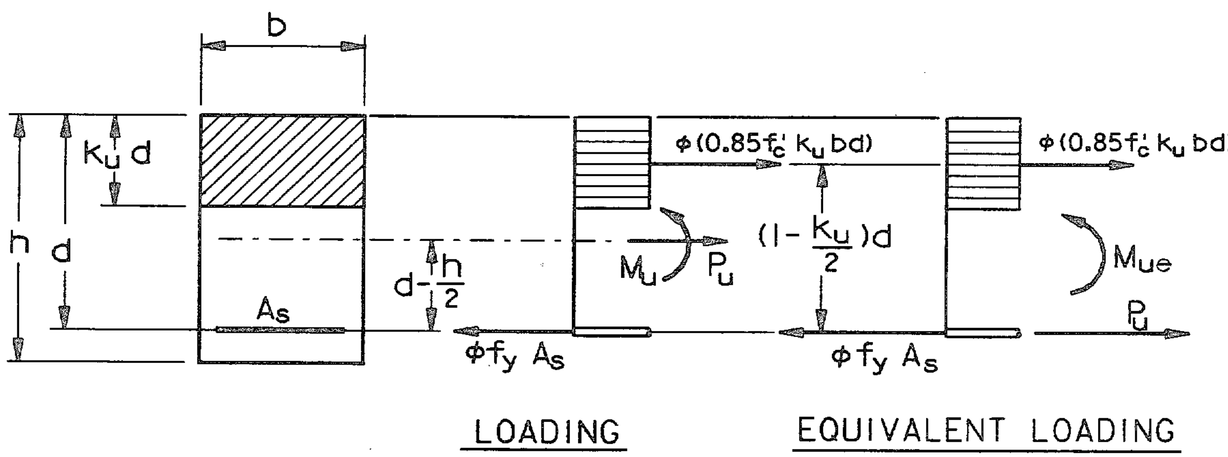
GIVEN : P_u, b, d, h, f_y, f'_c, ϕ (SEE DESIGN), A_s, $\rho \leq \rho_{MAX}$

FIND: k_u, M_{ue} AND M_u

$$k_u = \frac{\frac{P_u}{\phi bd} + f_y \rho}{0.85 f'_c} \quad , \quad M_{ue} = \left[0.85 f'_c k_u \left(1 - \frac{k_u}{2}\right) bd^2\right]\phi$$

$$M_u = M_{ue} - P_u\left(d - \frac{h}{2}\right)$$

Figure 9-3. Rectangular member, bending with small axial compression load, no compression reinforcement



FOR EQUIVALENT LOADING: $M_{ue} = M_u - P_u(d - \frac{h}{2})$

DESIGN

GIVEN : $P_u, M_u, b, d, h, f_y, f'_c, \phi = 0.9$

FIND: k_u, A_s, AND ρ

$$k_u = 1 - \sqrt{1 - \frac{M_{ue}}{0.425\,\phi f'_c bd^2}} \qquad A_s = \frac{0.85 f'_c k_u bd + \frac{P_u}{\phi}}{f_y}$$

$$\rho = \frac{0.85 f'_c k_u + \frac{P_u}{\phi bd}}{f_y} \le \rho_{MAX}$$

INVESTIGATION

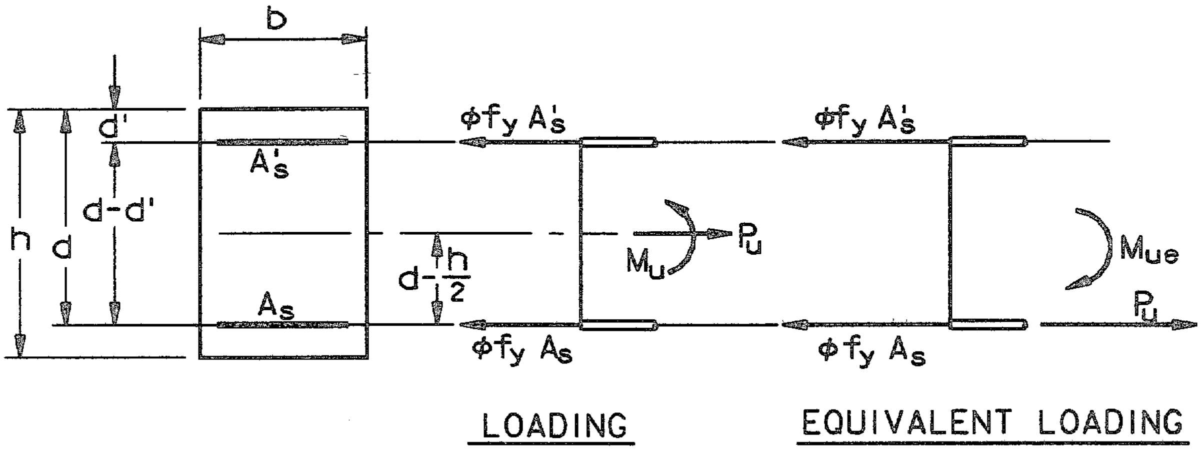
GIVEN : $P_u, b, d, h, f_y, f'_c, \phi, A_s, \rho < \rho_{MAX}$

FIND: k_u, M_{ue}, AND M_u

$$k_u = \frac{f_y \rho - \frac{P_u}{\phi bd}}{0.85 f'_c}, \quad M_{ue} = [0.85 f'_c k_u (1 - \frac{k_u}{2})\, bd^2]\phi$$

$$M_u = M_{ue} + P_u(d - \frac{h}{2})$$

Figure 9-4. Rectangular member, bending with axial tensile load, where $M_u/P_u \ge (d - h/2)$



FOR EQUIVALENT LOADING: $M_{ue} = -M_u + P_u\,(d-\frac{h}{2})$

DESIGN

GIVEN : P_u, M_u, b, d, h, f_y, f'_c, $\phi = 0.9$

FIND: A_s AND A'_s

$$A_s = \frac{\frac{P_u}{\phi} - f_y A'_s}{f_y} \quad , \quad A'_s = \frac{M_{ue}}{\phi f_y (d-d')}$$

INVESTIGATION

GIVEN : P_u, b, d, h, f_y, f'_c, $\phi = 0.9$, A_s AND A'_s

FIND: M_{ue}, M_u AND f'_s (STRESS IN A'_s)

$$M_{ue} = (P_u - \phi f_y A_s)(d-d')$$

$$M_u = P_u\,(d-\frac{h}{2}) - M_{ue}$$

$$f'_s = \frac{\frac{P_u}{\phi} - f_y A_s}{A'_s}$$

(NOT NECESSARILY EQUAL TO f_y. $f'_s \le f_y$ IS CRITERIA.)

Figure 9-5. Rectangular member, bending with axial tensile load, where $M_u/P_u < (d - h/2)$

and λ is 0.25 for hydraulic structures, compared to a value of 0.75 allowed by the ACI Building Code. Equation 9-13 is valid only for flexure.

(b) Design aids that will provide essentially the same results as the equations given in Figures 9-2 through 9-5 may be found in ACI publication SP-17. These will be valid for hydraulic structures so long as λ does not exceed 0.25 and the allowable capacity of the cross section is limited by flexural tension. Computer program CSTR (X0066) can assist in the design or investigation of strength of members in hydraulic structures (Appendix O).

d. Structures Not Subject to Hydraulic Action--Strength and Serviceability. The strength and serviceability requirements for structures not subject to hydraulic action should be in accordance with the current ACI Building Code. Computer program CASTR (X0067) can assist in the design or investigation of strength of members in walls not subject to hydraulic action (Appendix O).

e. Structures Not Subject to Hydraulic Action--Reinforced Concrete Design. Limits on strain, reinforcement, and concrete stress should be in accordance with the current ACI Building Code.

f. Shear Strength. The shear strength V_c provided by concrete should be computed in accordance with the ACI Building Code requirements. For cantilever retaining walls the maximum factored shear force should be computed at a distance d from the base of the stem for stem design, at a distance d from the stem for toe design, at the face of the stem for heel design, and at the top of the key for key design. Wherever an L-shaped wall without a toe is used, the shear force should be computed at the base of the stem for stem design and at the face of the stem for heel design.

9-9. Foundation Analyses. Foundation analysis should be performed in accordance with the methods described in Chapters 4 and 5 and illustrated in Appendix N. Concrete design should be for earth pressures corresponding to loading conditions which produce maximum tension in the respective elements of the foundation slab based on factored ultimate loads. The loading conditions corresponding to SMF = 2/3 should be considered as a minimum for single wedge analysis. This does not preclude the use of any other rational method of analysis that will produce an equivalent design.